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ORIGINAL ARTICLE

A New Methodological Contribution for the Geodiversity Assessment: Applicability to Ceará State (Brazil)

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Abstract The concept of geodiversity aggregates the abiotic elements of nature and promotes the geoconservation. The main objective of this work is to contribute to the upgrade of the method for the assessment and quantification of geodiversity proposed by Pereira et al. (2013). The method is based on the superposition of a regular grid of 12 × 12 km on different maps (lithology, geomorphology, soil, paleonthology, mineral and geological energy resources) at scales of 1:250,000 to 1:600,000. In addition to other upgrades, the water resources are regarded here as a new component to consider when quantifying geodiversity. The sum of these maps generated the quantitative Map of Geodiversity Indices and the Map of Geodiversity Assessment, ranging from very low to very high geodiversity. The analysis of the geodiversity map of the State of Ceará (Brazil) shows the applicability and advantage of this method, highlighting two regions with higher levels of geodiversity (Northwest and South) and another region with the lowest levels (Sertões Cearenses). The results also allowed the characterization of the State of Ceará concerning the individual components of the geodiversity, especially the water resources. Geodiversity indices and maps are comprehensive and user-friendly data in the territorial planning, considering the geodiversity either as a whole, or each of its components, especially the more sensitive such as fossil conservation, and water, mineral, and non-renewable energy resources management.

Keywords Geodiversity · Water resources · Ceará · Assessment · Territorial planning · Territorial management

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Introduction

The concept of geodiversity, as well as any other concept that is developed in the core of scientific knowledge, has gone and will still go through a process of conceptual self-affirmation. The concept has not had entire implementation yet, even in the geosciences domain, since the term only came into existence for the first time in 1991 during the international meeting of geoconservation (Brilha 2005; Panizza 2007), and, in the UK, in 1993, during the Malvern Conference on Geological and Landscape Conservation (Sharples 1993; Dixon 1995; Kiernan 1994; Burek and Porter 2002; Gray 2004; Zwoliński 2004; Serrano and Flaño 2007). The earliest references to the concept of geodiversity are found in Sharples (1995), Eberhard (1997), and Fishman et al. (1998).

After almost 25 years of existence, there are still some questions about its definition, since it embraces different approaches about what geodiversity is (Carcavilla 2012), or because the concept does not converge to a precise and unique definition within the same perspective, as Nieto (2001) stated. Consequently, it may be considered a developing concept that needs time to achieve its consolidation, but might not fall too far from the concept and ideas developed by Gray (2004, 2013).

According to Gray (2004), the term “geodiversity” can be defined simply as “the natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (land form, physical processes), soil features, their assemblages, relationships, properties, interpretations and systems.” Subsequently, the hydrological aspects were included by Zwolinski (2004) and (Gray 2013). According to Gray (2008), the concept of geodiversity has achieved acceptance and international use in the last years and now has reached the status of scientific paradigm within the scope of geosciences. Besides this holistic view, there are currently other approaches, predominantly geological and/or geomorphological (Sharples 1993, 1995, 1997, 2002; Nieto 2001, 2004; Nieto et al. 2006; Brilha 2005, 2016; Carcavilla et al. 2007; Carcavilla 2012; Zwolinski 2014). This concept has been increasingly used in the scientific literature, papers on geoheritage and geoconservation (Carcavilla et al. 2007; Brilha 2016). Another approach blends biotic and abiotic elements to make an indivisible piece on which the concept is based (Durán et al. 1998, 2005; Eberhard 1997; Leser 1997; Arribas and Durán 1998; Barthlott et al. 1999; Erikstad 1999; Johansson et al. 1999; Jedicke 2001; Stanley 2002; Australian Heritage Commission 2002; Kozlowski 2004; Santucci 2005; Parks and Mulligan 2010; Gray 2004, 2008, 2011, 2012, 2013; Forte 2014; Anderson et al. 2015; Najwer et al. 2016).

Hjort et al. (2012, 2015), based on the analyses of Gray (2004, 2011) and Beggs (2013), describes the integration between geodiversity, climate diversity, and biodiversity as an integral part of the ecosystems services. They also discuss the existing relationship between the main components and the values of geodiversity (Gray 2004).

In the last decades, some studies have contributed to the development of methods and techniques for the quantification of geodiversity (Serrano and Flaño 2007; Carcavilla et al. 2007; Zwoliński 2004, 2008, 2009; Ruban 2010, 2011; Dmitry 2010; Knight 2011; Manosso 2012; Pellitero 2012; Pereira et al. 2013; Silva et al. 2013, 2015; Bradbury 2014; Forte, 2014).

In addition to the scientific, cultural, and aesthetic values of geodiversity, functional and economic values are also important. Thus, evaluation of geodiversity should focus not only on conservation of fossils, rare rocks and minerals, landforms and landscapes, but also on the management of mineral, nonrenewable energy resources, and water resources, which are essential to the development of human activities. The method presented henceforth has been developed in this perspective, providing comprehensive and user-friendly geodiversity data. It is intended that the generated indices and maps could be used as tool for nature conservation and management of natural resources in the scope of territorial planning.

Study Area

The State of Ceará is located in the northeast of Brazil. Its limits are the Atlantic Ocean to the north and northeast, the States of Rio Grande do Norte and Paraiba to the east, and Pernambuco and Piauí to the southwest. The state has an area of 148,886 km^2, corresponding to 1.74% of the surface of Brazil (IBGE 2015) (Fig. 1).

The geology of the State of Ceará includes about 74% (108,000 km^2) of ancient igneous and metamorphic rocks. This geological domain corresponds to the whole central portion of the state and is mostly bordered by the Paleozoic and Mesozoic sedimentary rocks that form the basins of Araripe (south), Parnaíba (west), and Apodi (east), in addition to the quaternary sediments in the coastal waters (north).

According to several studies on the geomorphology (e.g., Ab'saber 1969, 1974; Mabesoone 1978; Castro 1979; Souza et al. 1988; Peulvast and Sales 2004; Sales and Peulvast 2007; FUNCEME 2009), the State of Ceará consists of several domains of plateaus, coastal plains, alluvial plains, and residual landforms. There is a large spatial predominance of the low altitude plateaus of the Sertaneja Depression, resulting from the long action of the erosive and denudational processes that promoted the flattening of the Precambrian igneous-metamorphic basement (Brandão 2014).

The regional climate of the Cerá State presents significant variations, but a semiarid climate marked by prolonged periods of drought is predominant in about 92% of the territory. As a result, the hydrological regime is characterized by the intermittence of the watercourses, which normally flow in the rainy season and dry in the drought season (Brandão 2014).

Geodiversity Assessment Method

Data Input

The method for the quantification of geodiversity developed by Pereira et al. (2013) was based on the use of a regular grid of 25 × 25 km placed on a set of maps in order to quantify the diversity of lithological, geomorphological, soil, mineral, and paleontological elements. Taking into account the map scales of the Ceará State, a new grid size of 12 × 12 km was considered to enable the most accurate differentiation of results, which is related to the maximum range between the highest and lowest Geodiversity Index values. Other major upgrades of this study are the revision of the method for counting the paleontological diversity, and the insertion of the water resources diversity as one of the elements for the quantification of geodiversity (Fig. 2).

The values obtained for the six partial indices were equalized to five classes from the Natural Breaks classifier (jenks) before the final sum.

All the procedures of this upgrade for examining and counting were carried out using Arcgis 10.1 and 2.6.1 Qgis software and the following digital maps:

– Geological map at 1:500,000 (CPRM 2008), for the counting of lithology and fossil records;
– Geomorphological map at scale 1:250,000 (IBGE 2015), for the counting of geomorphological units;

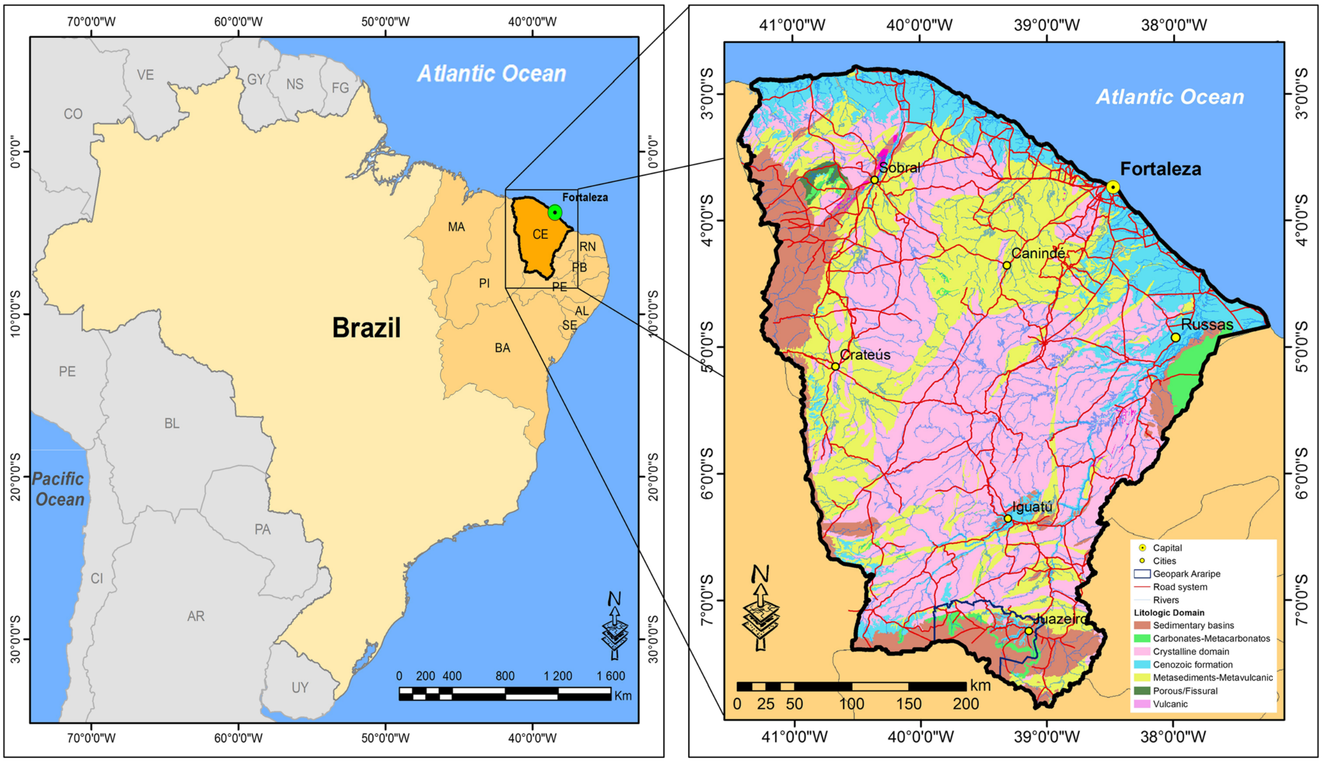


Fig. 1 Location and main lithological domains of Ceará State (adapted from IBGE 2015)

– Soil map at the scale 1:600,000 (IBGE 2015), for the counting of soil elements;
– Mineral and geological energy resources map in shapefile format from the CPRM (2008) database at scale 1:500,000, for the counting of different occurrences.

For the water resources analysis, four new maps were generated:

– Annual average precipitation map from mathematical and statistical calculations of quantitative raw data available

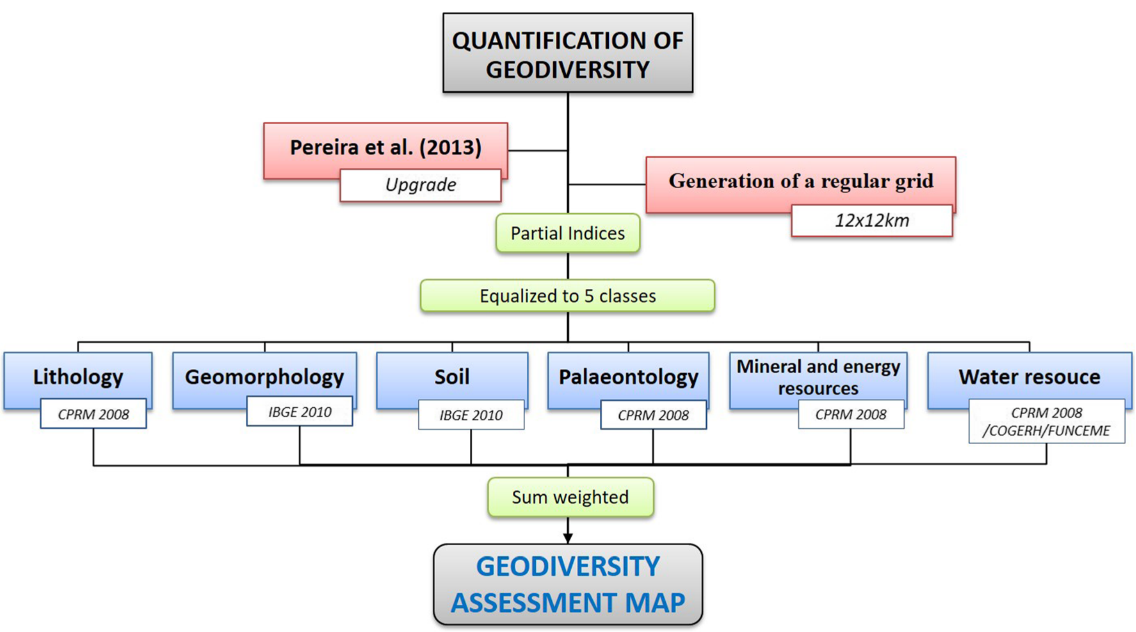


Fig. 2 Flowchart for the geodiversity quantification

on the database of state and federal agencies (COGERH 2014);
- Groundwater specific flow map based on CPRM (2008);
- Hierarchy of rivers; from the DTM, the fluvial channels were extracted through semi-automatic calculation, so that Strahler's (1957) hierarchical classification of channels could be employed;
- Water reservoirs based on IBGE (2015).

Analyses

The spatial analysis was performed on each theme, by counting the number of occurrences of spatial attributes in each of the 1107 cells (e.g., number of geological units) (Fig. 3), generating six partial indices of diversity. The partial indices were then summed up to make up the Geodiversity Index.

For the quantification of lithological diversity, the following geoprocessing steps were followed:

- The lithological units were homogenized, in order to eliminate duplication of polygons of the same lithology within each cell while counting them using Arcgis (Fig. 4a);
- Reclassification of textual information into numeric information, to be used in the stage of quantification of lithological units by cell;
- Correlation between the lithology and the grid cells from the reclassified values for each lithology, integrating them to the grid that corresponds to the areas of each cell;
- Computing the values of lithological occurrences per cell, using the polygons of each lithology type as a reference (Fig. 3);
- Modeling of the values obtained from the map generation with the partial indices of diversity.

The method for the geomorphological diversity quantification is a simplified version of the original method of Pereira et al. (2013) and Silva et al. (2013, 2015), serving the main purpose of creating a new index of water resources. For this calculation, the 3rd taxonomic units—Geomorphologic Units (IBGE 2009)—were computed (Fig. 4b). The procedures for quantification are the same as those used to obtain the lithologic index.

For the soil diversity, the number of occurrences of different soil types by cell was computed, following the same procedures used to compute the lithological diversity (Fig. 4c).

For the mineral and geological energy resources diversity (Fig. 4d), the number of different occurrences per cell was counted (Fig. 5). The re-occurrence was not computed, as defined by Pereira et al. (2013).

Two methods were tested for the quantification of paleontological diversity; the method 1 (Fig. 6a, b) considers the number of geological units with the presence or potential presence of fossils, excluding other formations which do not bear fossils (Pereira et al. 2013, Silva et al. 2013, 2015). The method 2 that is now proposed considers the total number of species or genera of fossils that are accounted in a cell, based on the data available in the scientific literature (Cassab 2015; Carvalho and Santos 2005; Souza et al. 2008; Campos 2011; Fambrini et al. 2011, 2013; Barroso 2012) (Fig. 6c, d). The map generated by the method of counting the number of described species or genera presents greater detail and greater range between minimum and maximum number of occurrences. Therefore, this was the

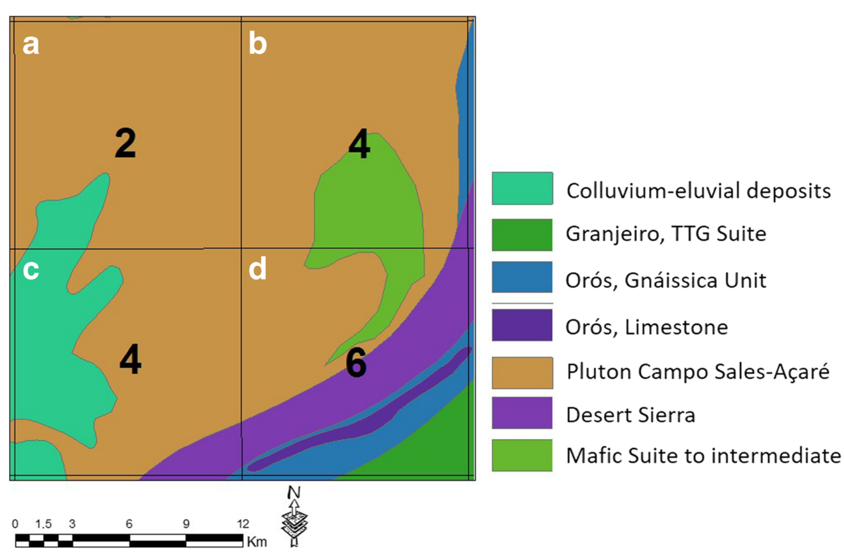
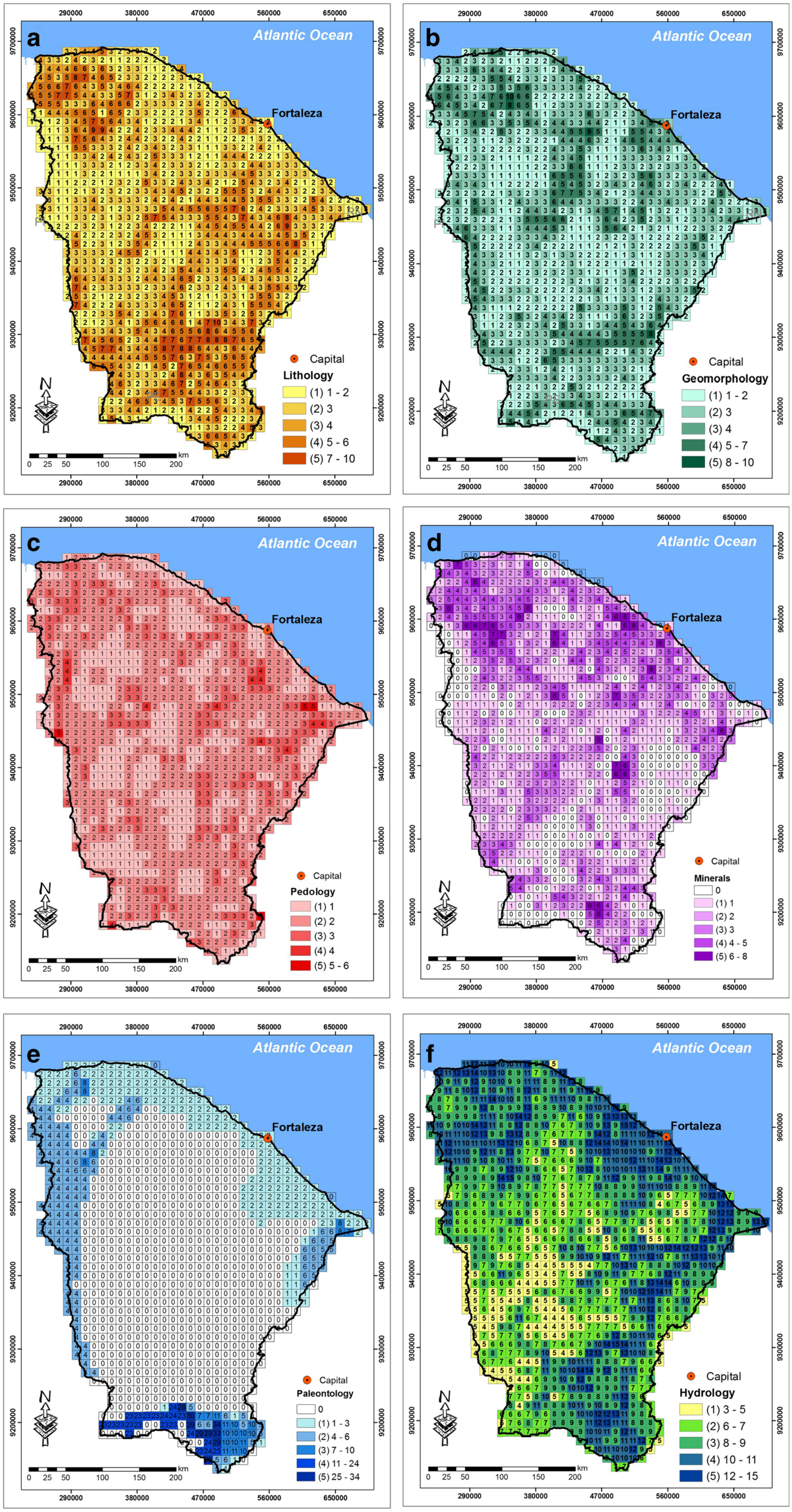


Fig. 3 Example of quantification of the lithological diversity index in the 12 × 12 km grid. Seven different lithologies are represented: *A* = two occurrences; *B* = four occurrences; *C* = four events; *D* = six occurrences


a
Atlantic Ocean
Fortaleza
Capital
Lithology
(1) 1 - 2
(2) 3
(3) 4
(4) 5 - 6
(5) 7 - 10
b
Atlantic Ocean
Fortaleza
Capital
Geomorphology
(1) 1 - 2
(2) 3
(3) 4
(4) 5 - 7
(5) 8 - 10
c
Atlantic Ocean
Fortaleza
Capital
Pedology
(1) 1
(2) 2
(3) 3
(4) 4
(5) 5 - 6
d
Atlantic Ocean
Fortaleza
Capital
Minerals
0
(1) 1
(2) 2
(3) 3
(4) 4 - 5
(5) 6 - 8
e
Atlantic Ocean
Fortaleza
Capital
Paleontology
0
(1) 1 - 3
(2) 4 - 6
(3) 7 - 10
(4) 11 - 24
(5) 25 - 34
f
Atlantic Ocean
Fortaleza
Capital
Hydrology
(1) 3 - 5
(2) 6 - 7
(3) 8 - 9
(4) 10 - 11
(5) 12 - 15
N
km
0 25 50 100 150 200
290000 380000 470000 560000 650000
9700000 9600000 9500000 9400000 9300000 9200000

◀ **Fig. 4** Maps of partial diversity indexes. **a** Map of lithological diversity. **b** Map of geomorphological diversity. **c** Map of soil diversity. **d** Map of mineral and energy diversity. **e** Map of paleontological diversity. **f** Map water resources diversity

method used for the final calculation of the paleontological diversity and geodiversity.

The water resources index of diversity results from the sum and normalization of four sub-indices (Fig. 7). The steps for the preparation of the map of water resources diversity are described as follows:

1. Sum of the grid and rainfall map. In order to make a model of the distribution of average rainfall per cell, the amount of rainfall considered was the one recorded in the centroid of each cell.
2. Sum of the grid and the groundwater specific flow map. In order to obtain a single value of specific flow in each cell, the weighted average of the specific flow rates was calculated and applied to data modeling.
3. Sum of the grid and the map of water reservoirs. The relative area of water reservoirs was calculated in each cell and classified into five categories for subsequent data modeling.
4. Sum of the grids and map of river hierarchy. The quantification of the channel hierarchy considered the highest existing hierarchy within the grid. Data were classified into five categories and data modeling was applied.
5. Sum of the rainfall, specific groundflow, rivers hierarchy, and water reservoirs indices, in order to obtain the Water Resources Diversity Map (Fig. 8).

In the analysis of partial maps, it is observed that rainfall has a direct influence in the final outcome of the Water

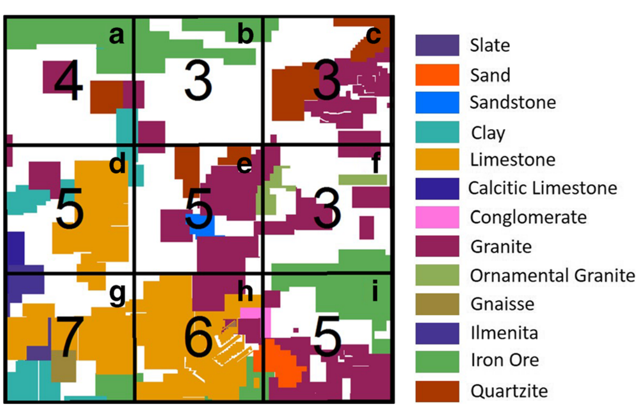


Fig. 5 Example of the quantification of the mineralogical diversity index in the 12 × 12 km grid. Thirteen different minerals are represented, with the smallest occurrence found in *B*, *C*, and *F* = three events and the higher occurrence in *G* with seven instances

Resources Index (Figs. 7a and 8). It also indirectly influences the values of other partial indices. For example, the groundwater specific flow is both a result of the geological formations, and the water storage provided by precipitation. It should be notice that the Water Resources Index Map expresses the average of four indicators.

The Geodiversity Indices Map (Fig. 9) results from the sum of the six maps of partial diversity (Table 1—raw data). The total raw value of this sum was reclassified by the Jenks method, which recalculates and redistributes the values taking into consideration the desired number of classes. The partial geodiversity indices varied from one to five classes (Table 1—reclassified data), thus determining equal weights among the diversity indices for the subsequent sum (Sum of the reclassified data). The total set of data was normalized and the modeling was carried out, using the data taken from the centroids of each cell.

For the generation of the Geodiversity Assessment Map (Fig. 10), the total values of geodiversity index were imported from the ArcGis Join tool and attached to the table in the vector file of the centroids of each cell. Subsequently, the Gaussian kriging interpolation method was used in order to calculate the specific values, correlating them with the nearest neighbors, thus generating intermediate values between the centroids.

In the interpolation process, for a more detailed analysis, a histogram of the distribution of the geodiversity indices was designed (Fig. 11). The histogram displays the range of values and its distribution of the analyzed space. Each bar of the histogram represents sets of class intervals of the geodiversity indices. Data distribution shows asymmetry to the right, which represents a concentration of areas with values between indices 7 and 14 in the territory. The highest bars (10 and 11) represent the greater concentration of geodiversity rates.

Results

Lithological Diversity

The lithological diversity ranged from 1 to 10 (Fig. 4a). The greater diversity occurs in the Ceará northwest and central-south regions, where a considerable number of cells present very high diversity (7–10). The Sertões Cearenses in the central-western region is a large area with lower values of lithological diversity.

The diversity of the northwestern portion may be explained by the presence of the Médio Coreaú Domain, a folded belt (orogenic belt), where lithologies of different ages (Torquato and Neto 1996) can be found. The most important lithology corresponds to the São Joaquim Group, of approximately 2200–2300 Ma, which comprises gneiss, migmatite, and quartzite. Moreover, the Médio Coreaú Domain presents

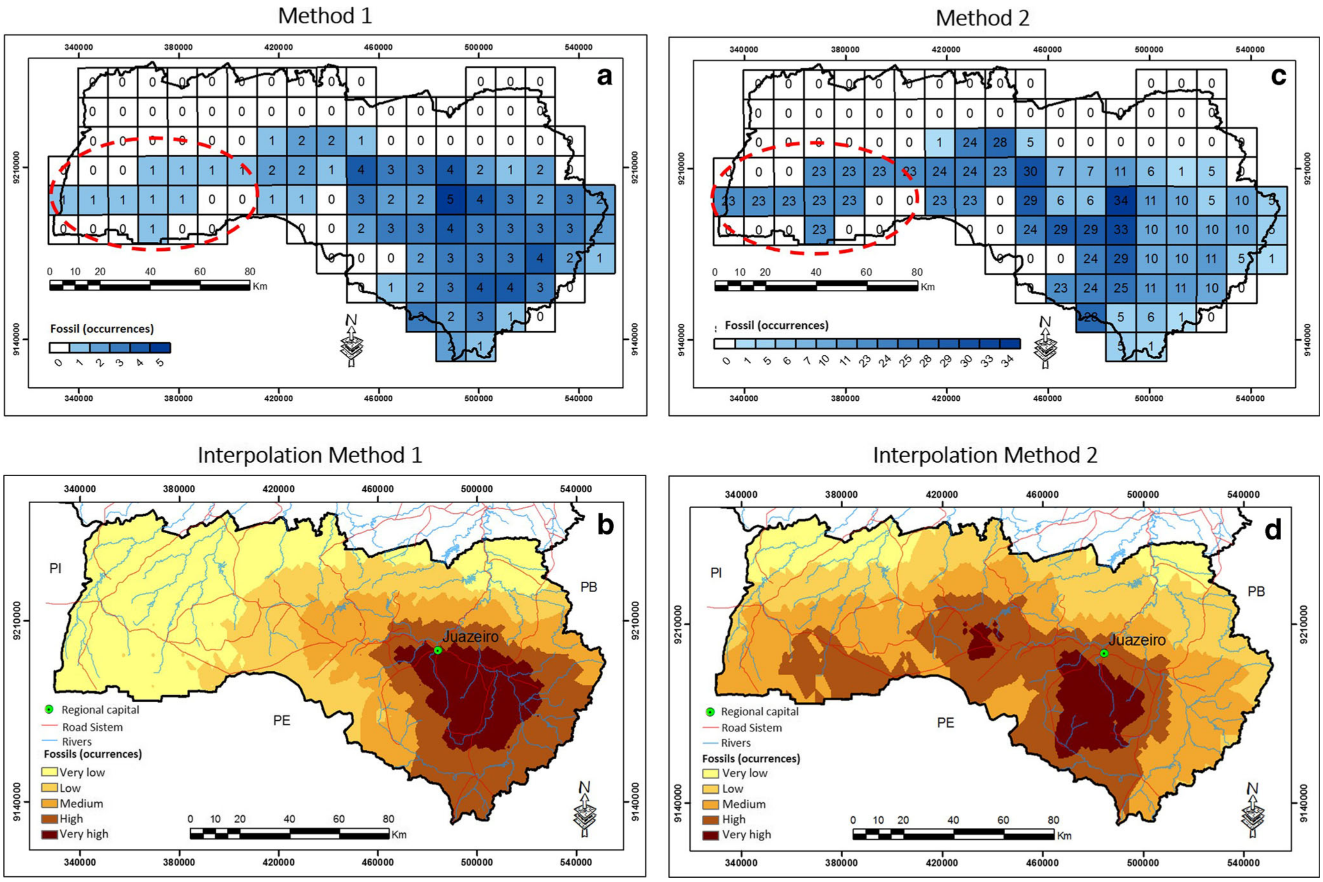


Fig. 6 Maps of indices and of paleontological assessment of the south of Ceará sector. **a** Map of the paleontological indices based on the number of fossiliferous sedimentary rock units per cell; **b** Gaussian kriging interpolation. **c** Map of paleontological indices based on the sum of fossil occurrences by lithological formation in the cells; **d** Gaussian kriging interpolation by method 2

major faulting and Precambrian lineaments. This structure corresponds to the segment called Transbrasilian Lineament, which crosses the whole country from its NE edge to its extreme SW border, and represents a Proterozoic suture area between Brazil and Africa (Silva Filho et al. 2007). The diversity presented in the central-south region of Ceará is explained by the fact that it is made up of a complex of Archean-Proterozoic rocks, with structural features and granitoid plutonism directly related to the Brasilian Orogenic Cycle (Neoproterozoic) (Bendelak 2004).

Geomorphological Diversity

The geomorphological diversity range from 4 to 10 by the non-reclassified values and the higher values are distributed in almost the entire State of Ceará territory (Fig. 4b). However, the highest geomorphological diversity is found in the northwest and north regions, as well as in the central-south Ceará and the Fortaleza Metropolitan area.

The high geomorphological diversity in the northwest region is explained by tectonic factors that have generated important geomorphological elements (Claudino-Sales and Lira 2011). Among these, the following stand out:

– The Ibiapaba Sierra and the escarpment of the Paleozoic sedimentary basin of Parnaiba, dominated by the Serra Grande Formation;
– The Médio Coreaú system, with eroded Precambrian structures, which have gone through long evolution, especially in the phases of the Brasilian Orogenetic Cycle, at the end of Precambrian, when Brazil and Africa amalgamated, generating the Pannotia megacontinent. This process produced extensive folding and faulting, along with regional metamorphism and magmatism, during the Pannotia fragmentation in the early Paleozoic, which resulted in the formation of the sedimentary basin of Parnaiba.

The diversity in the north and in the Metropolitan area of Fortaleza is related to the variability of landforms of four geomorphological domains (Brandão 2014):

– The Coastal Plains that present a diverse set of depositional relief patterns of eolian, fluvial, and marine

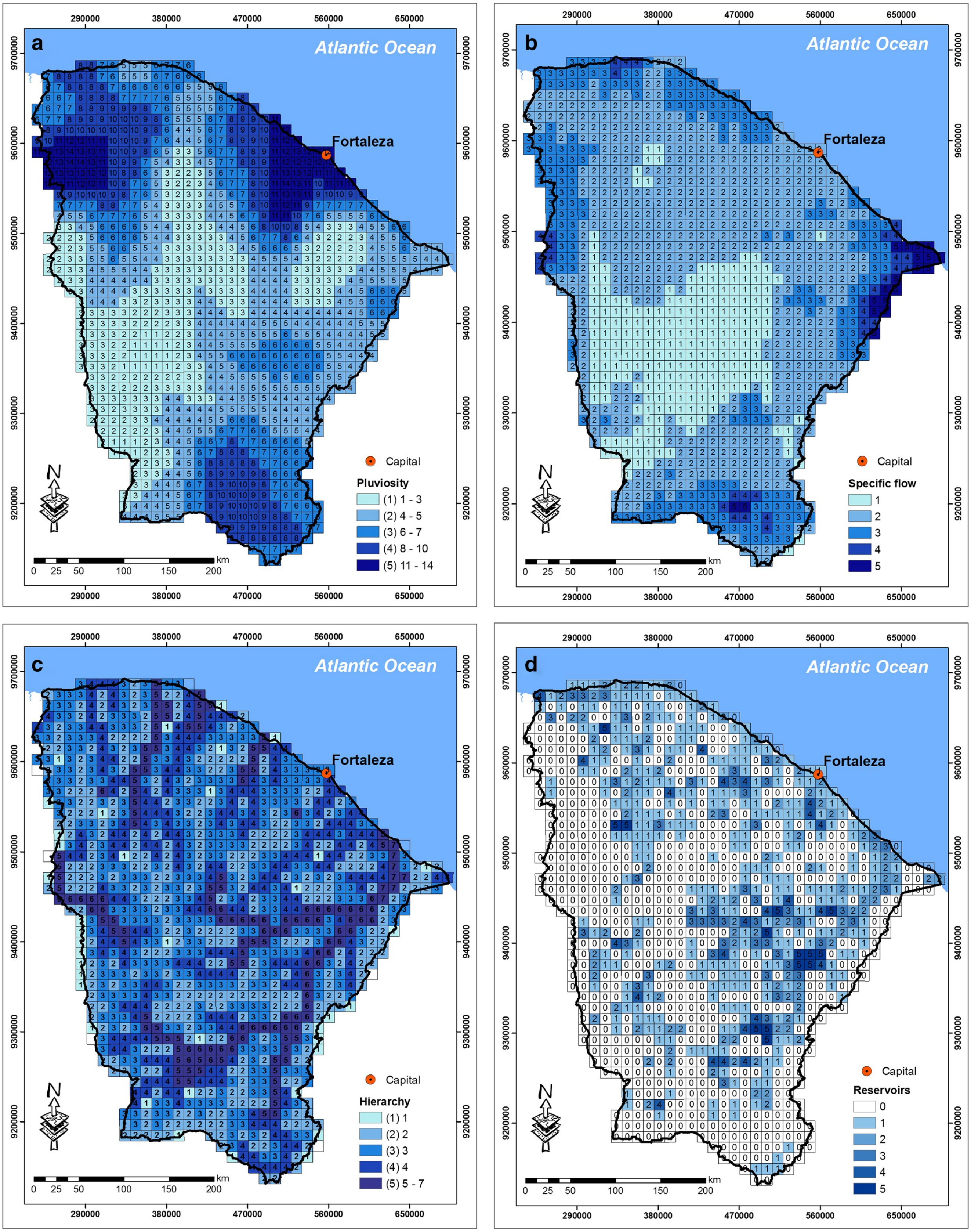


Fig. 7 Maps of partial indices of water resources diversity generated from the 12 × 12 km grid. **a** rainfall; **b** groundwater specific flow; **c** rivers hierarchy; **d** water reservoirs

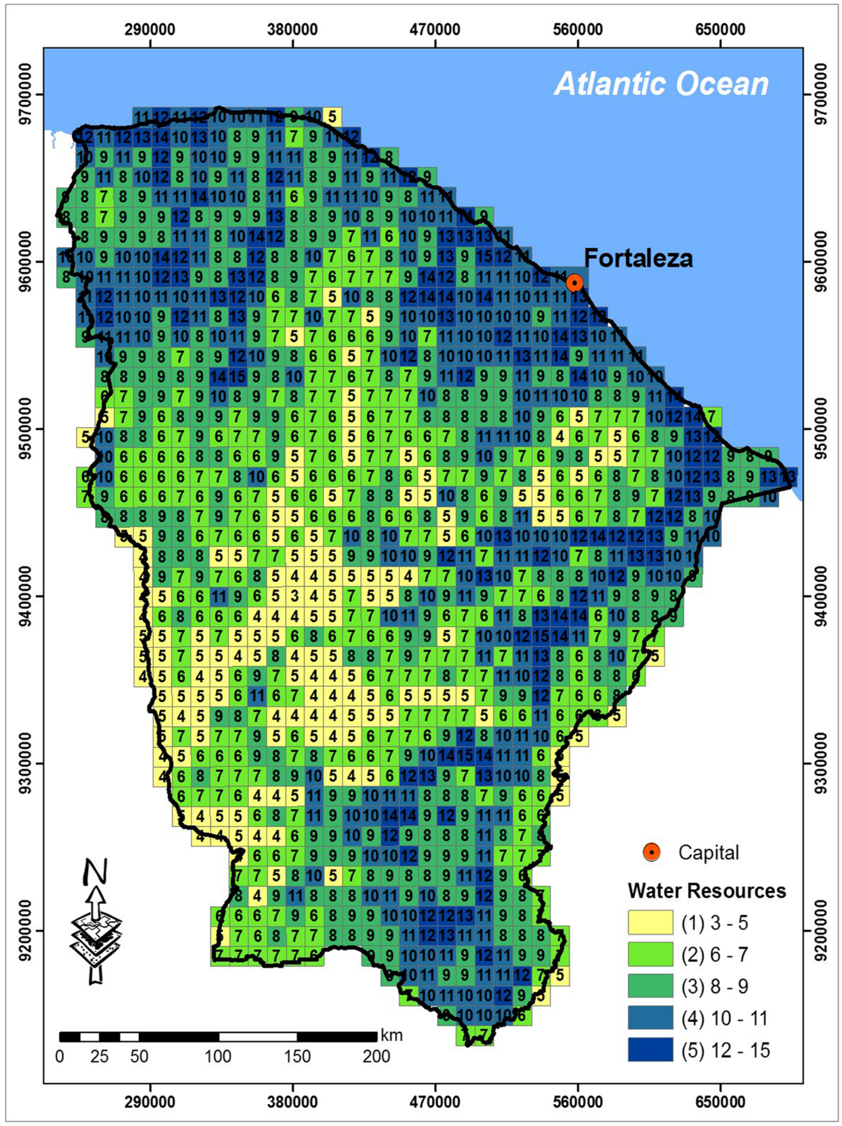


Fig. 8 Map of Water Resources Indices of the State of Ceará, obtained from the sum of the maps of Fig. 5. The subtitles indicate the normalized values (*1* to *5*) and the non-normalized values *3* to *15*

origins, such as the dune fields and fluvial-to-marine plains, in the form of mangroves at the delta of the main rivers;

– The Residual Landforms of large dimension, reaching high altitudes (between 600 and 1100 m);
– The Coastal Tablelands consisting of extensive flat tops on sedimentary rocks, which represent ancient depositional surfaces, featuring extremely smooth gradients towards the shoreline;
– The Sertaneja Depressions, a set of plateaus that have been incipiently dissected by a low-density drainage system, and extensive pediments located at the foot of the cuestas and scarps (Brandão 2014).

The geomorphological diversity identified in the Ceará central-south region is explained by the presence of important geomorphological domains such as the Sertaneja Surface, the Residual Massifs, and the Sertaneja Depression. Different landforms are related with Jurassic-Cretaceous basins and Precambrian basement (Brito Neves et al. 2000; Peulvast and Sales 2008).

Soil Diversity

The final values of soil diversity range between 1 and 6 (Fig. 4c). The higher soil indices are sparsely distributed throughout the Ceará State (Fig. 4c). However, they are concentrated in the northeastern portion of the state, where the Apodi Plateau is located. This plateau is known by the gathering of cambisols, fluvisols, and vertisols in the fluvial plain, and litholic neosols at the boundary between the low and the

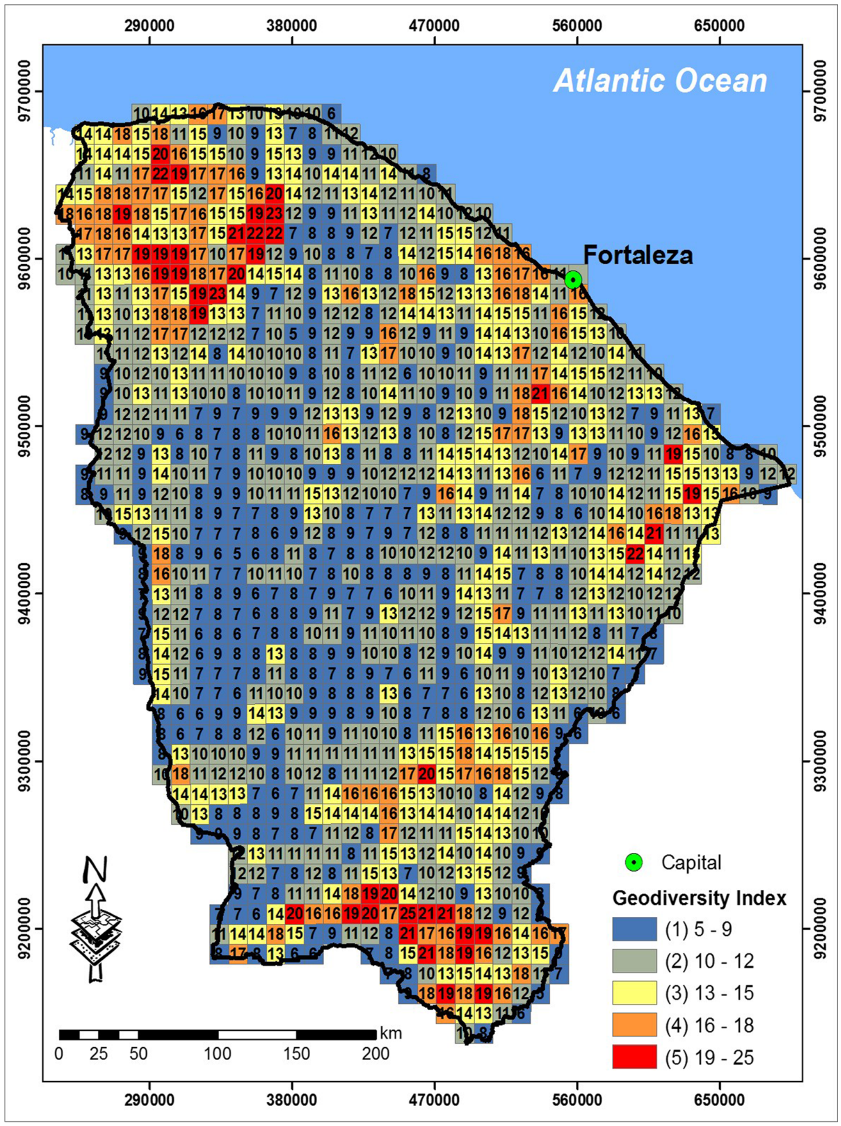


Fig. 9 Map of the Geodiversity Indices resulting from the sum of the maps of diversity indices

medium Jaguaribe River and the edges and uplands of the Potiguar basin (Maia 2005).

Mineral and Geological Energy Resources Diversity

The map of mineral and geological energy resources diversity shows that the higher values are concentrated mostly in the northern region, and occasionally in the central and southern areas of the state (Fig. 4d).

The results show, as expected, a relationship between the mineral diversities and the lithology (Fig. 4a, d). Ceara's northwest and northern mineralogical wealth stands out associated with the gneiss-migmatitic Proterozoic formations that evolved from the Paleoproterozoic protolith (Vidal et al. 2005). In the northwest of the state, the Granja Complex (sedimentary/igneous derived gneisses, partly migmatitic) concentrates the main sources of ornamental rocks, which are sparse in the central and southern regions.

Paleontological Diversity

Located in the south region of the Ceará State, the Araripe Basin is one of the largest Cretaceous fossil-bearing deposits known worldwide. Among the most important paleontological formations of the region is the Santana Formation. It is 50 to 180 m thick and was deposited in an estuary with restricted seawater circulation, suggested by the presence of gypsum lenses (Sampaio 2001).

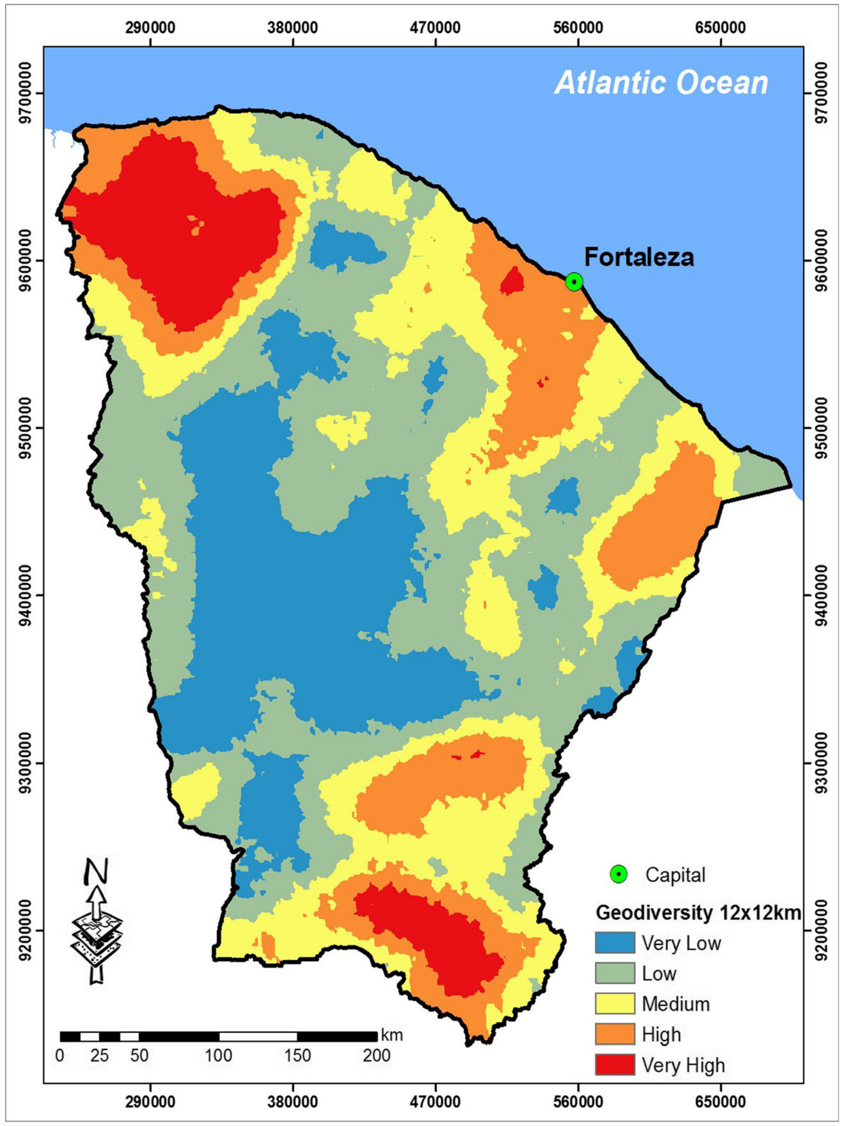
Water Resources Diversity

The high values of the Water Resources Index are mainly concentrated in the northern, eastern, and southern sectors of the state. These characteristics are mainly associated with more significant rainfall in these areas, as well as with factors such as a higher concentration of groundwater specific flow rates, higher flow rates of rivers, represented by major rivers

Table 1 Table excerpt of the descendant values from partial diversity indices total geodiversity. It shows the highest and lowest values of the gross Geodiversity Index (in italics) and reclassified (boldfaced) from a total of 1107 cells

ID/(Q)	Lithological index		Paleontological index		Geomorphological index		Mineralogical index		Pedological index		Water resources index		Geodiversity index	
	Raw data	Reclass. data	Raw data	Reclass. data	Raw data	Reclass. data	Raw data	Reclass. data	Raw data	Reclass. data	Raw data	Reclass. data	Sum reclass. data	Total date normalized
1578	7	*5*	34	*5*	5	*4*	7	*5*	2	*2*	17	*4*	*25*	**5**
206	5	*5*	33	*2*	4	*4*	6	*4*	2	*3*	15	*5*	*23*	**5**
359	5	*5*	25	*2*	5	*4*	7	*5*	3	*2*	16	*5*	*23*	**5**
122	5	*5*	29	*2*	5	*2*	6	*5*	1	*3*	14	*5*	*22*	**5**
244	4	*4*	30	*2*	4	*4*	5	*4*	2	*3*	13	*5*	*22*	**5**
245	5	*4*	29	*2*	2	*4*	6	*5*	2	*2*	14	*5*	*22*	**5**
888	5	*5*	29	*1*	3	*4*	5	*4*	2	*3*	13	*5*	*22*	**5**
243	4	*4*	29	*2*	4	*5*	4	*4*	2	*2*	12	*4*	*21*	**5**
571	4	*4*	28	*1*	4	*4*	5	*4*	1	*4*	13	*4*	*21*	**5**
850	6	*4*	24	*2*	5	*4*	5	*4*	2	*2*	13	*5*	*21*	**5**
(…)	(…)	*(...)*	(…)	*(...)*	(…)	*(...)*	(…)	*(...)*	(…)	*(...)*	(…)	*(...)*	*(...)*	**(…)**
1220	1	*1*	0	*0*	1	*1*	0	*1*	1	*2*	5	*1*	*6*	**1**
1236	1	*1*	0	*0*	1	*1*	0	*1*	1	*2*	5	*1*	*6*	**1**
1570	1	*1*	0	*0*	1	*1*	0	*1*	1	*1*	5	*2*	*6*	**1**
1650	1	*1*	0	*0*	1	*1*	0	*1*	1	*1*	4	*2*	*6*	**1**
1651	1	*1*	0	*0*	1	*1*	0	*1*	1	*1*	4	*2*	*6*	**1**
1779	1	*1*	0	*0*	1	*1*	0	*1*	1	*1*	4	*2*	*6*	**1**
441	1	*1*	0	*0*	1	*1*	0	*1*	1	*1*	4	*1*	*5*	**1**
867	1	*1*	0	*0*	1	*1*	0	*1*	1	*1*	4	*1*	*5*	**1**
1741	1	*1*	0	*0*	1	*1*	0	*1*	1	*1*	4	*1*	*5*	**1**

Fig. 10 Map of the Geodiversity Assessment of the state of Ceará, generated from the Gaussian kriging interpolation



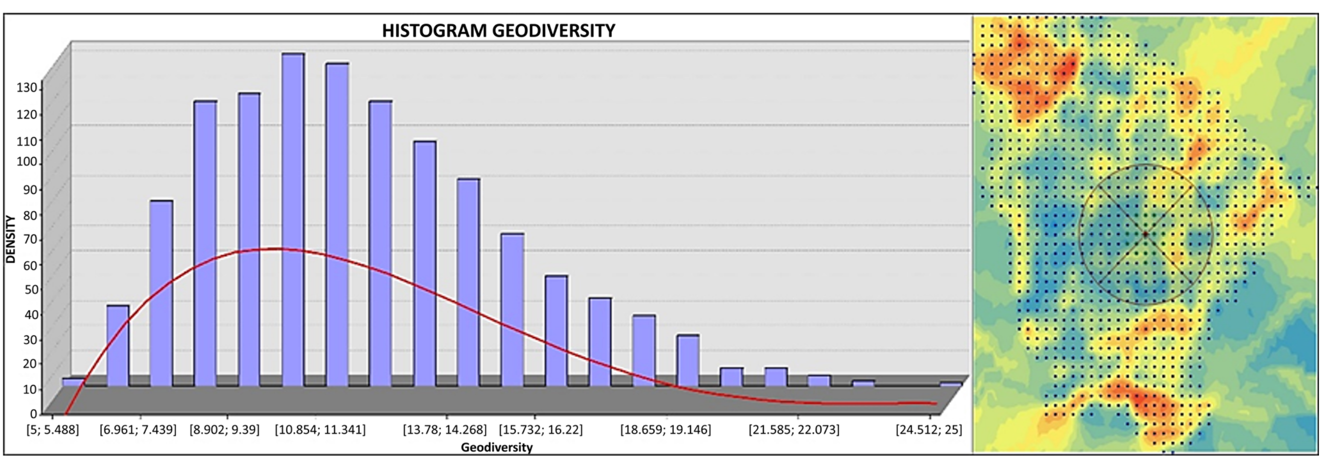


Fig. 11 Histogram of the Geodiversity Indices of the State of Ceará and the subproduct of the interpolation of geodiversity indices originated from the centroids

hierarchy derived from Strahler's (1957) classification, and also by larger water reservoirs.

For the analysis of the water resources indices, the high values (8–15) are distributed from the south, through the central-south region, to the northwest of Ceará, towards the coast. However, the highest values (10 to 15) are concentrated in the northwest and north of Ceará, as well as in the Metropolitan area of Fortaleza. The opposite occurs in the central-west region (Sertões Cearenses), which presents the lowest water resources indices (3 to 7).

Geodiversity

The areas that concentrate highest geodiversity values are located in the northwest and south regions of the state (Figs. 9 and 10). Some regions occasionally present high geodiversity, like the metropolitan area of Fortaleza. In the southern region, the Araripe Basin stands out with very high values of geodiversity, justified by high lithological, geomorphological, paleontological, and hydrological values (Fig. 4a, e, f).

A large area of the central-western region (Sertões Cearenses) is characterized by very low geodiversity, as a result of low or very low values of the partial indices. Areas with medium geodiversity rates are randomly distributed.

Conclusion

This research was conducted with the main objective of contributing to the improvement of the quantification of geodiversity, proposing an upgrade of a method that considers several components of geodiversity (Pereira et al. 2013). This upgrade includes water as a geodiversity component and the Water Resources Index in the set of indicators for the geodiversity evaluation. This indicator is especially important in territories with unequal distribution of water resources and supply problems in many regions, as the State of Ceará (Brazil).

In addition to the inclusion of this indicator, this work also presents a new procedure for the assessment of paleontological diversity. The counting of species and genera has been detailed, requiring the analysis of all available bibliographic data. However, in regions where paleontological heritage reveals great importance, such as the Araripe Basin, the precision of the method can contribute to a better management of resources and accurate conservation measures.

The upgrade of the method for geodiversity assessment presented in this work also makes possible to evaluate independently the lithological, geomorphological, paleontological, soil, mineral, and geological energy resources and, as we propose, water resources diversity. Each map may be seen individually as a relevant data set to be used in the detailed analysis of the elements in a given territory.

The interpolation procedure performed to obtain the Map of Geodiversity Assessment aimed to improve the representation and understanding of the geodiversity in a given area. This map, based on the polygons generated in the interpolation process, provides ordered scales of geodiversity, which facilitates reading comprehension by non-specialists, namely politicians and managers.

Overall, this proposal of method for the quantification of geodiversity mainly intends to serve as a technical tool for land use planning, including the designation of areas with geoconservation potential. It also serves as a basis for the discovery of new uses, such as in education and tourism, thus contributing to the recognition and protection of new potential areas for geoconservation.

The case study in the State of Ceará (Brazil) demonstrates the applicability of this assessment method. Northwestern and southern areas stand out with higher geodiversity, and the central area of Sertões Cearenses with the lower geodiversity. The results can be easily understood, looking the individual components of the geodiversity, especially the water resources and the paleontological diversity.

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